Concepts for efficient production, transport and cooling of intense muon beams

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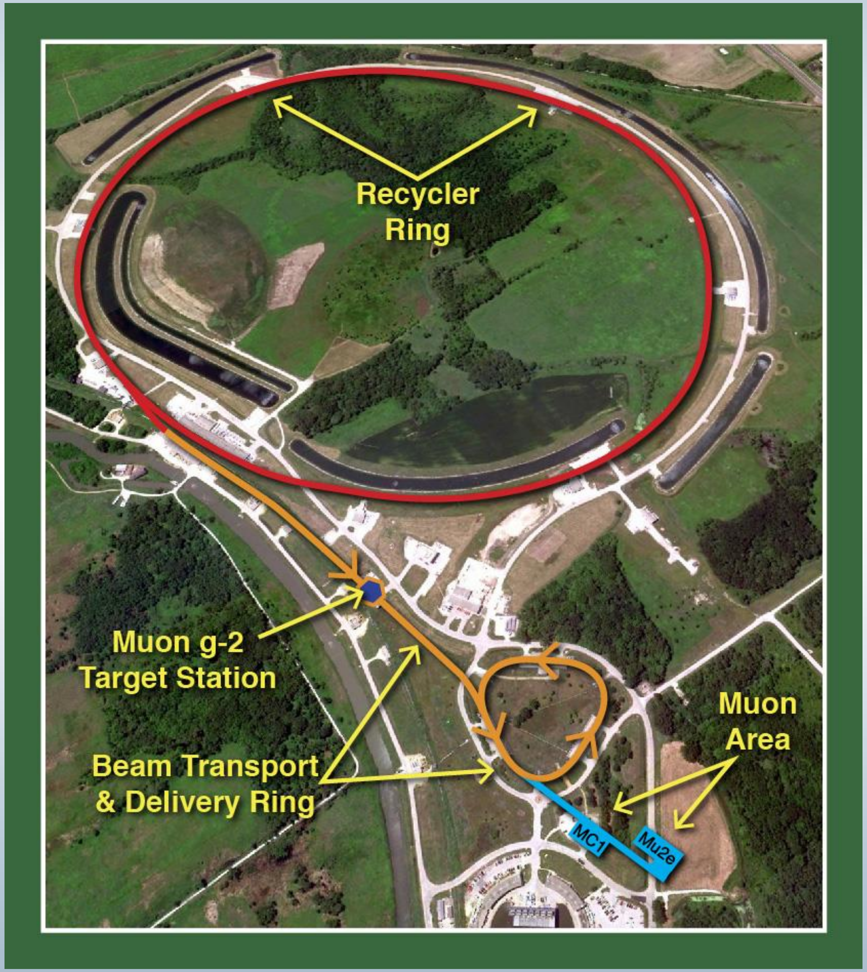
Accelerator Physics and Technology Seminar, Fermilab, Batavia, IL, USA

July 28, 2015

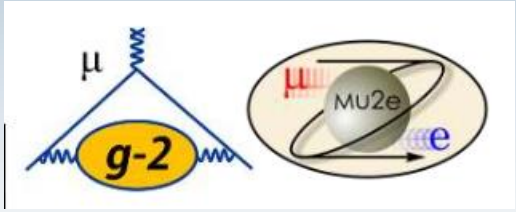
Why muons?

- Carry the same electrical charge as electrons
- Like electrons, muons are elementary particles and thus can produce “clean collisions”
- Muons are 207 times heavier than electrons making it more sensitive to the discovery of new physics
- Unlike electrons, they can be accelerated and stored in circular rings at very high (~TeV) energies by taking advantage of their larger mass

Current activity: Muon campus @ Fermilab



http://muon.fnal.gov/



- **Mu2e**: The Mu2e experiment attempts to detect charged lepton flavor violation
- **g-2**: Precision measurement of magnetic properties of muons

Far future (?): Towards a Muon Collider

- Some benefits…
  - Large muon mass suppresses synchrotron radiation
  - Muons can be accelerated and stored using rings at much higher energy than electrons
  - As with an e^+e^- collider, a $\mu^+\mu^-$ collider would offer a precision probe of fundamental interactions

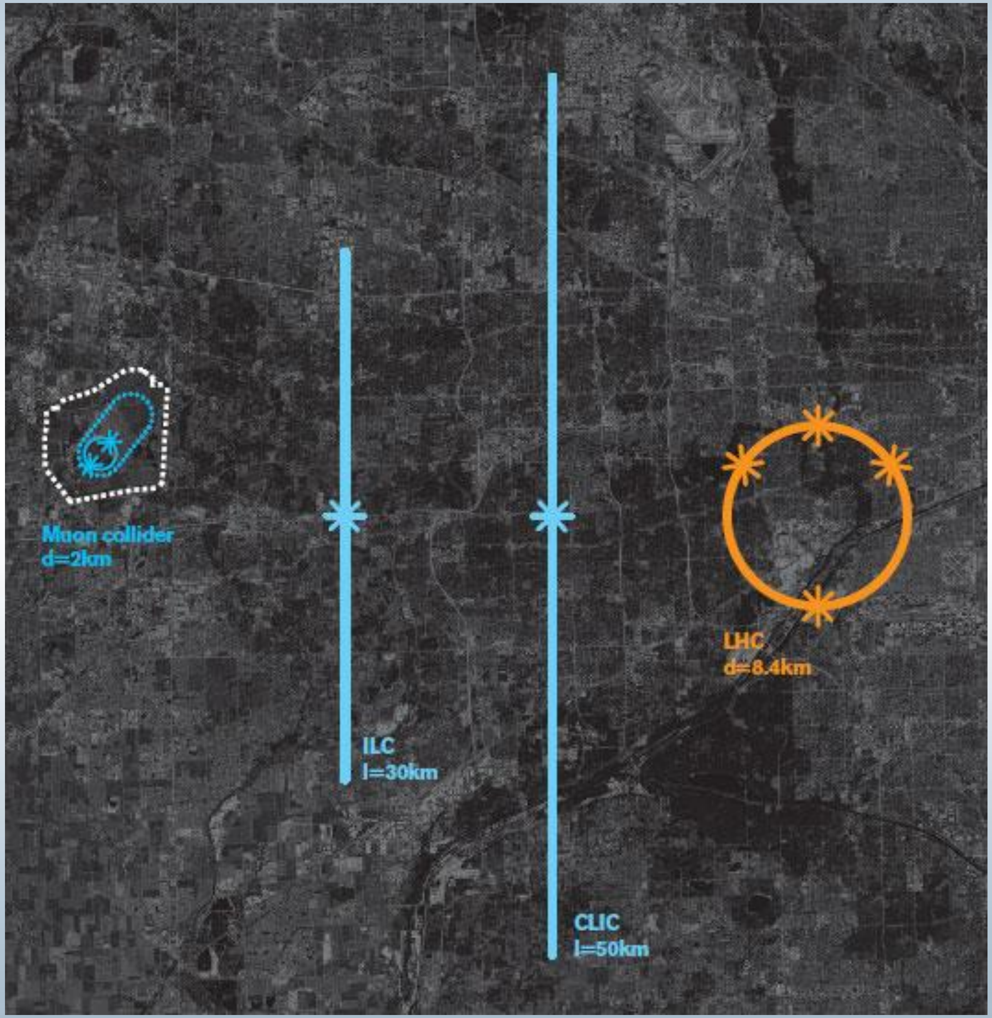


Image: www.map.fnal.gov

Muon Collider (MC) components

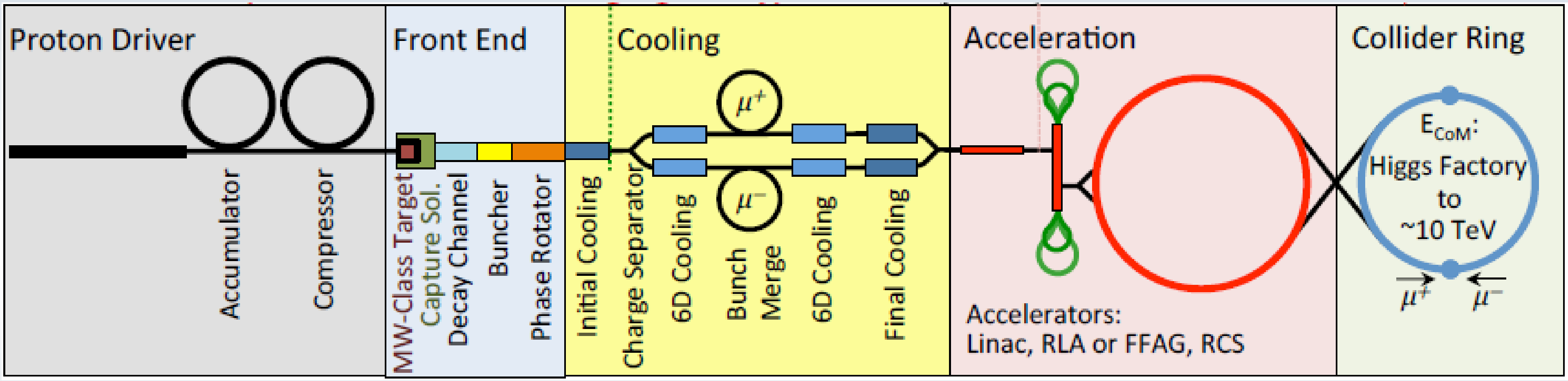


Image: www.map.fnal.gov

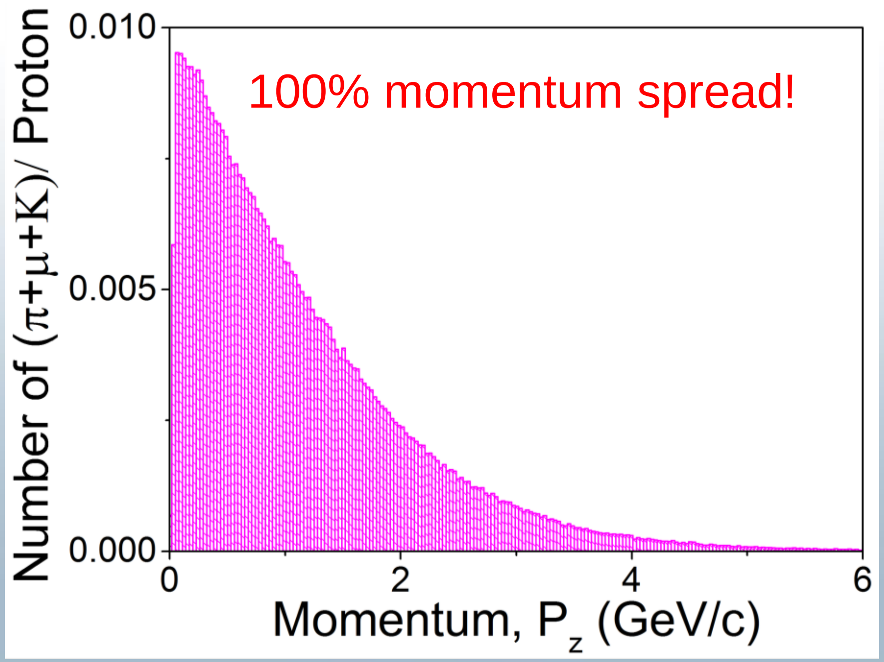
- The desired average luminosity of a MC is $O(10^{34})$ cm^{-2}s^{-1}

Challenge #1

- Muons born as tertiary beams: Protons → pions → muons
- To achieve the desired luminosity it will require the production of 10^{14} muons per second
- How to capture, manipulate and transport such intense muon beams?

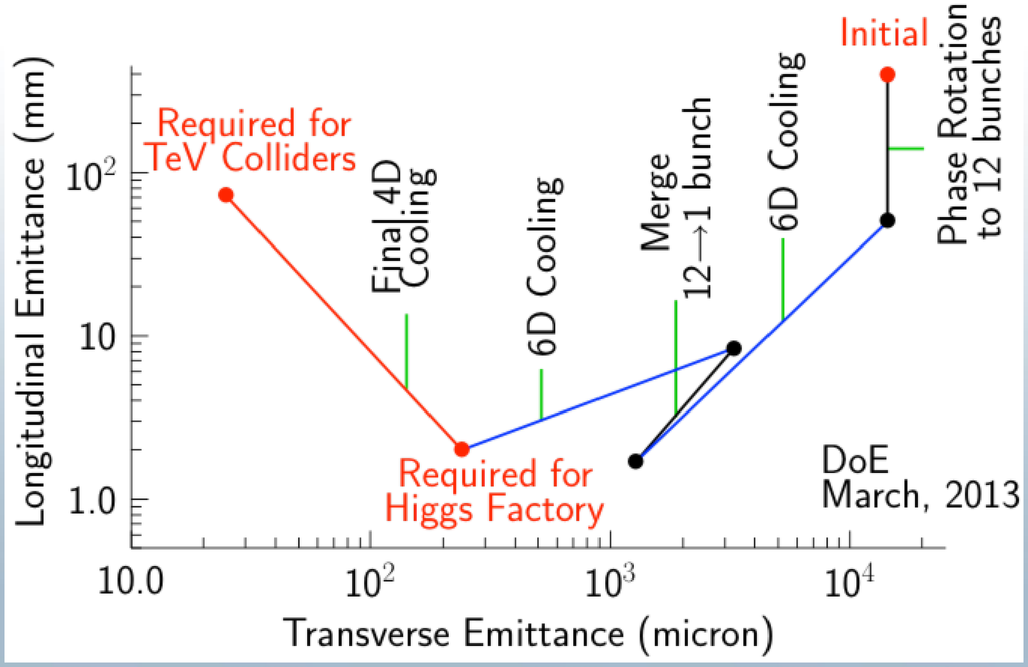
Proton Driver:

Parameter	Value
Power	4 MW
Repetition rate	15 Hz
Proton Energy	8 GeV
Protons per pulse	2.08×10^{14}
Rms pulse length	2 ns



Challenge #2

- Initial beam occupies a very large phase-space area
- To obtain luminosities O(10^{34}) $cm^{-2}s^{-1}$ we need to reduce the initial phase-space by several orders of magnitude
- How to cool the muon beam fast?

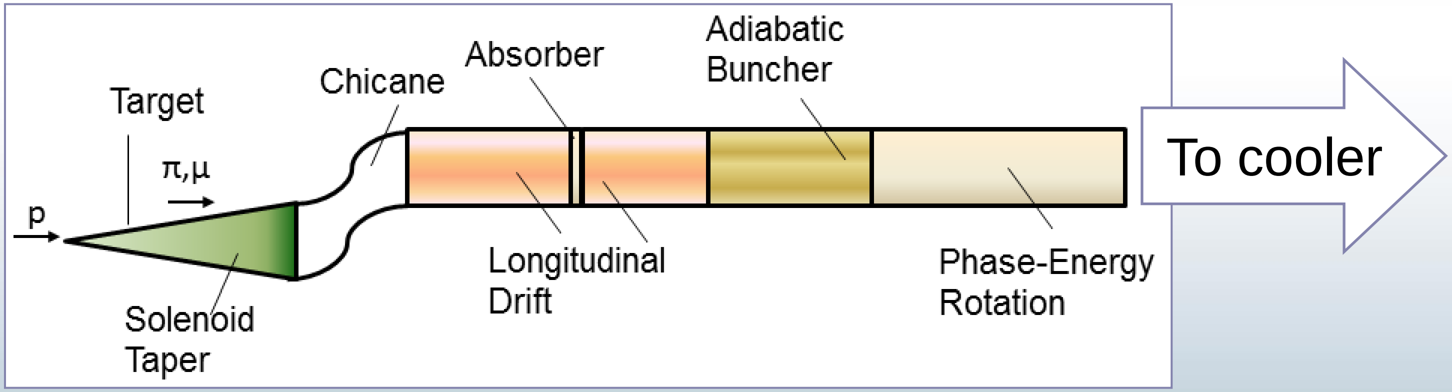


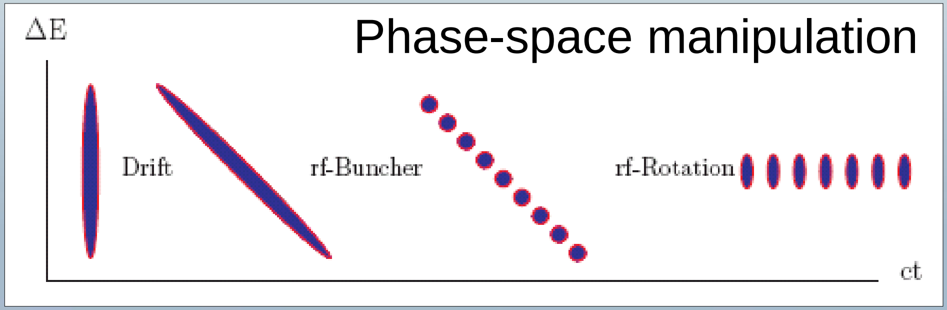
Purpose of this work

- Present a efficient scheme to produce, manipulate and transport a muon beam
- Present a simple scheme to cool the 6D emittance of a muon beam up to 5 orders of magnitude
- Simulate the aforementioned concepts and present the results
- Discuss challenges and future work
- Summary

Muon capture & transport scheme

- Capture muons that result from the pion decay that are produced by a intense proton beam impacting a target
- Manipulate the initial phase-space of these muons to make them well-suited to subsequent accelerator systems





Relevant paper: Editor's highlights!

- Our review paper, that was published in Journal of Physics G received special attention!

IOP Publishing — Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **41** (2014) 125002 (12pp) — doi:10.1088/0954-3899/41/12/125002

Compact muon production and collection scheme for high-energy physics experiments

Diktys Stratakis[1] **and David V Neuffer**[2]

[1] Brookhaven National Laboratory, Upton, NY 11973, USA
[2] Fermi National Accelerator Laboratory, Batavia, IL 60510, USA

Download: http://iopscience.iop.org/0954-3899/41/12/125002

Journal of Physics G

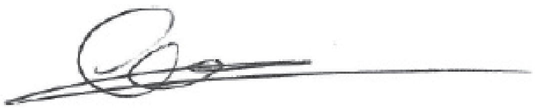
Nuclear and Particle Physics

This is to certify that the article

Compact muon production and collection scheme for high-energy physics experiments

by Diktys Stratakis and David V Neuffer

has been selected by the editors of *Journal of Physics G: Nuclear and Particle Physics* for inclusion in the exclusive 'Highlights of 2014' collection. Papers are chosen on the basis of referee endorsement, novelty, scientific impact and broadness of appeal.

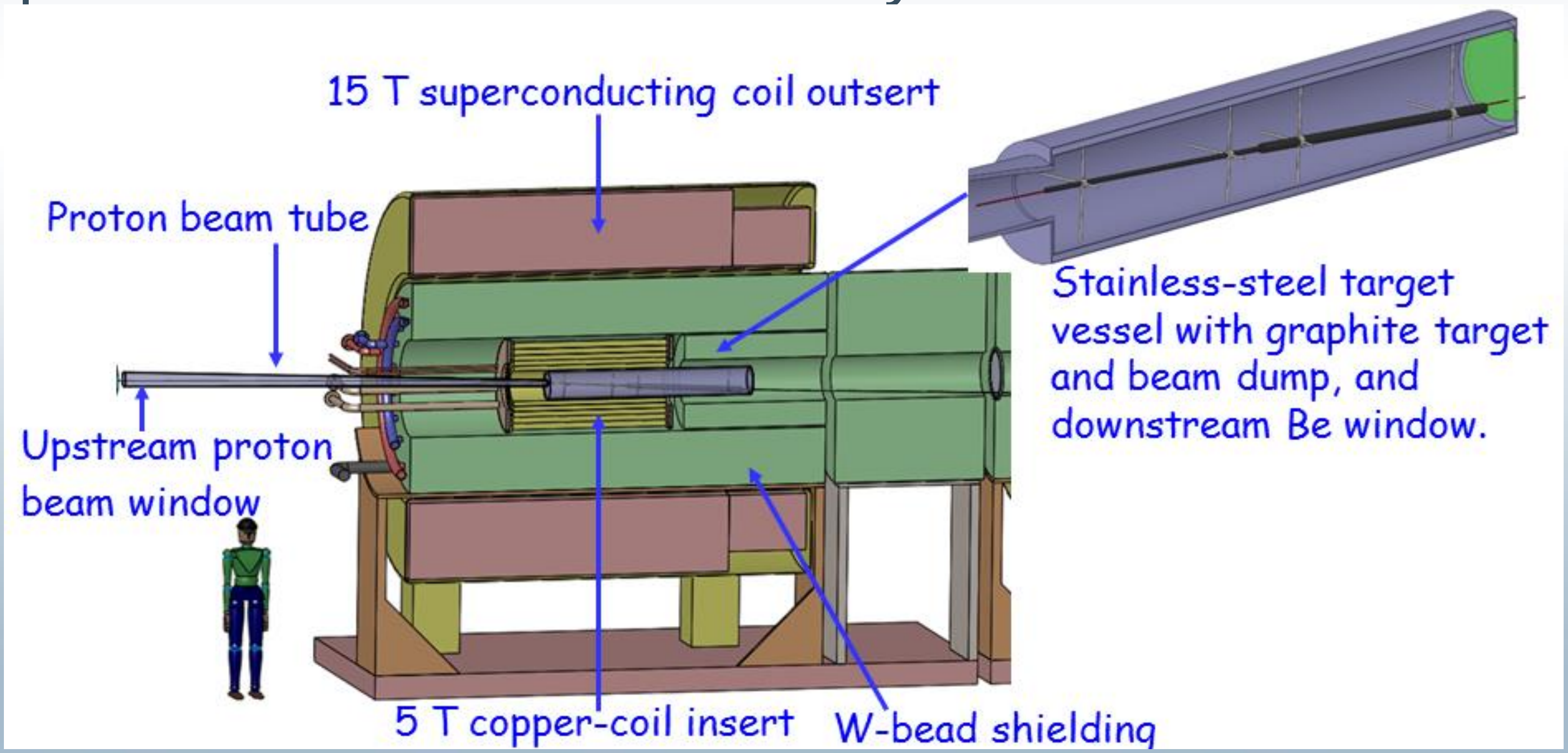


Colin Adcock
Publisher
Journal of Physics G: Nuclear and Particle Physics
iopscience.org/jphysg

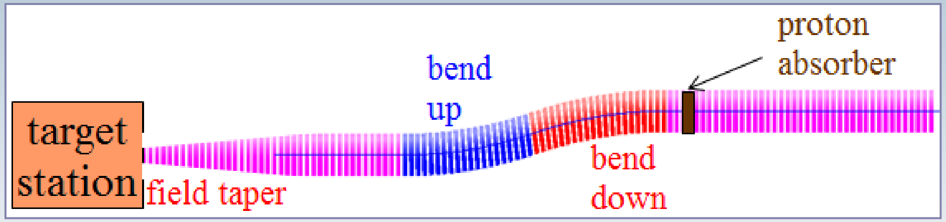
IOP Publishing

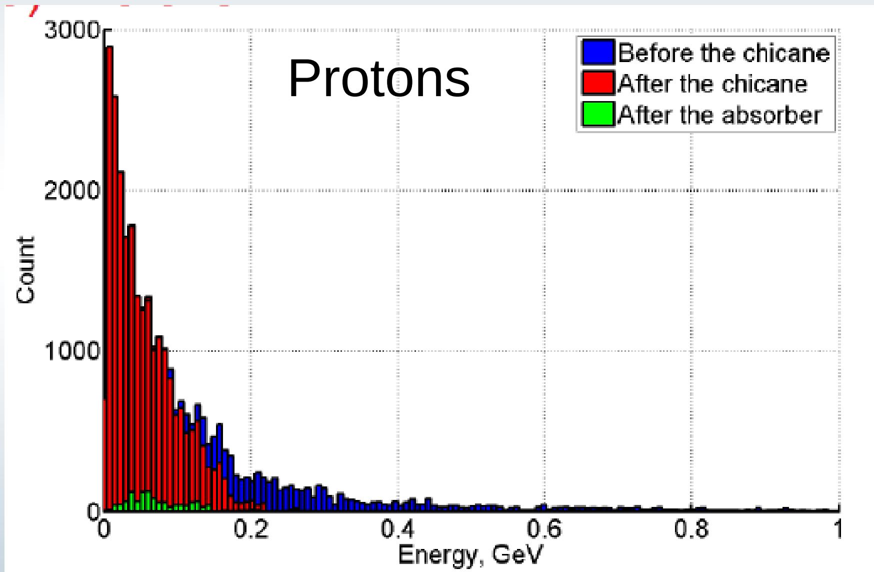
Muon capture

- Target immersed in a 20 T solenoid that collects both μ^+ μ^-
- Target and proton beam tilted with magnetic axis
- Optimized for maximum muon yield at 40<KE<180 MeV



Handling of secondary particles

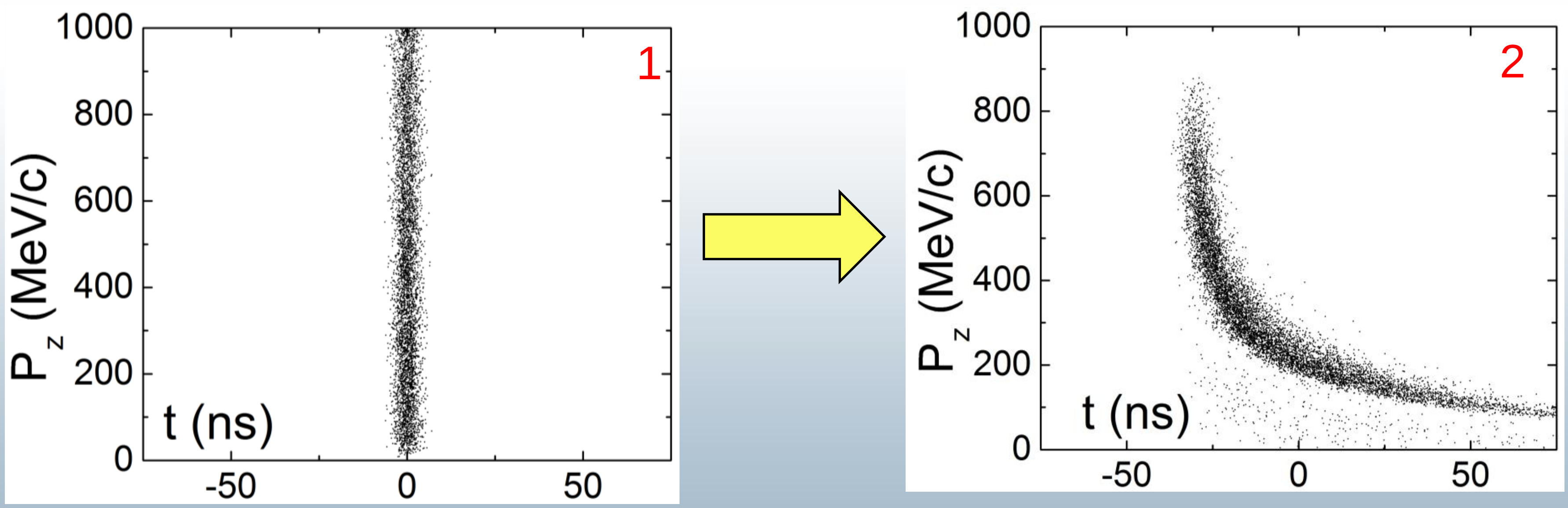




- Bend solenoidal chicane induce dispersion to the beam so that high momentum particles scrape
- Proton absorber to remove low momentum protons

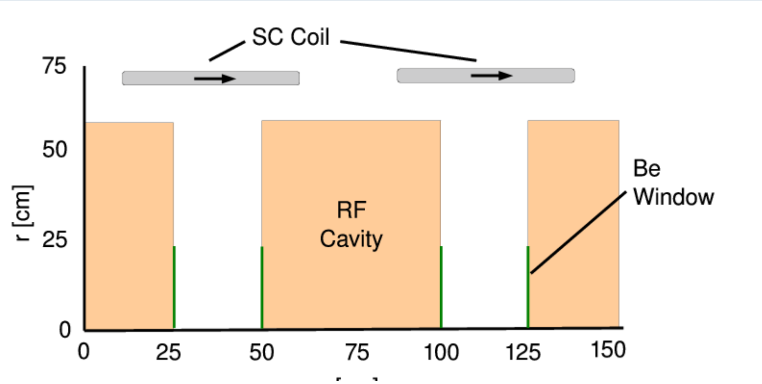
Bunching & phase-rotation (1)

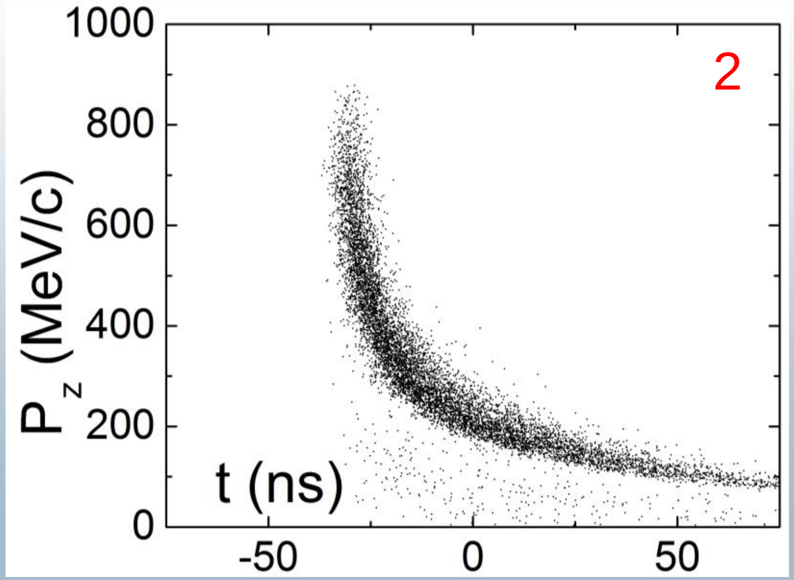
- After target, the beam is allowed to lengthen and develop a energy-time correlation [1→2]

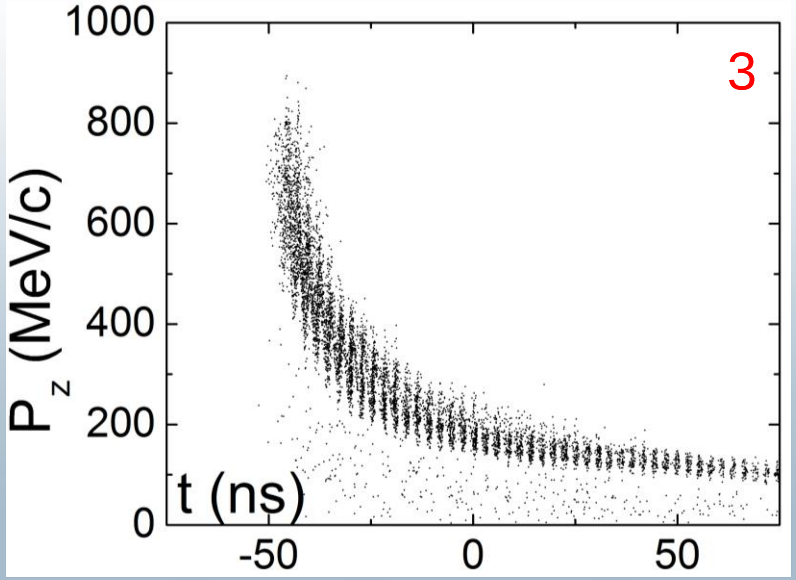


Bunching & phase-rotation (2)

- Bunching with a set of rf cavities whose frequencies drop with distance (490-360 MHz) [2→3]

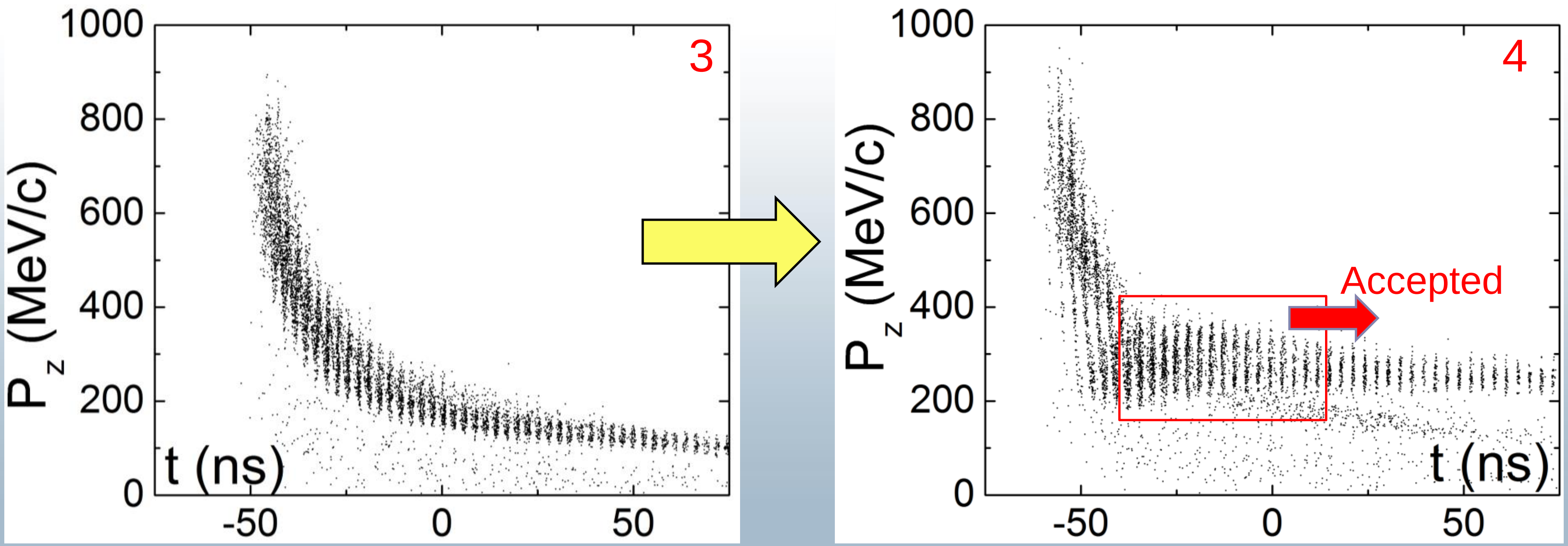






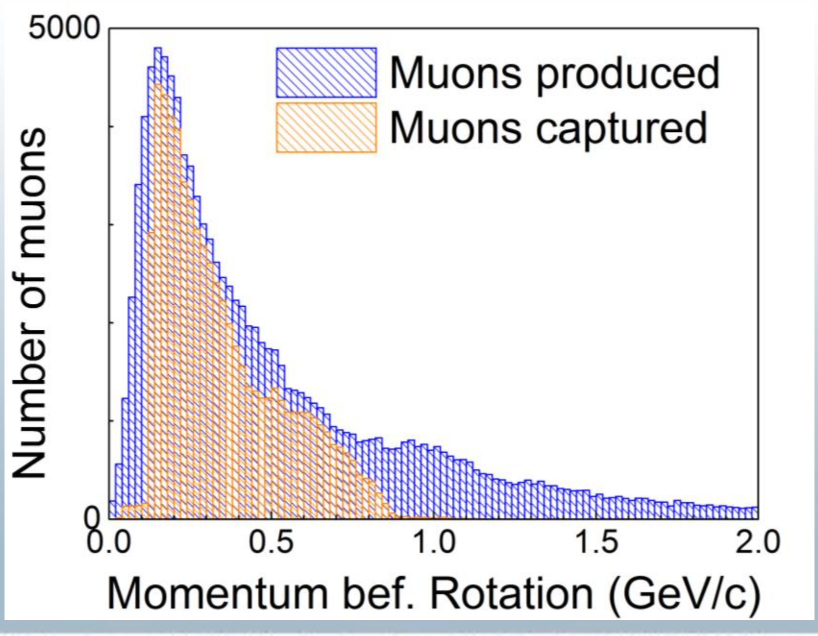
Bunching & phase-rotation (3)

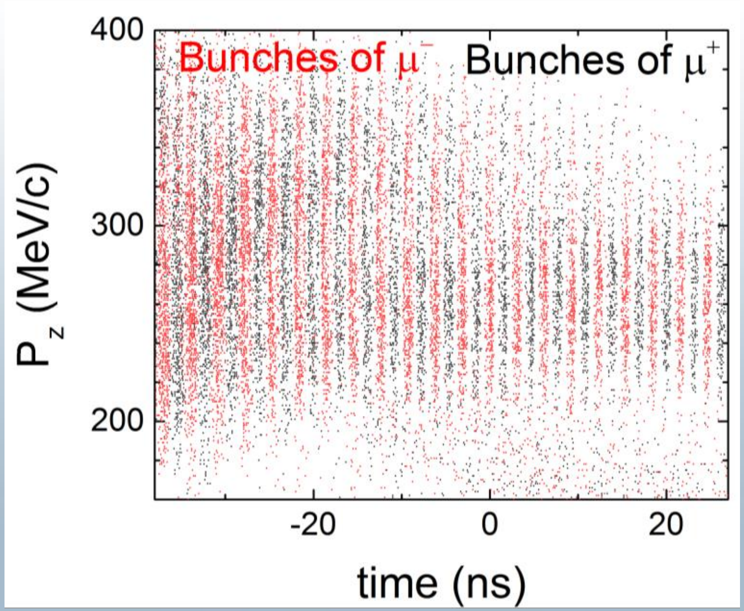
- After bunching, the beam is phase-rotated with a second set of rf cavities with decreasing frequencies (360-326 MHz) [3→4]



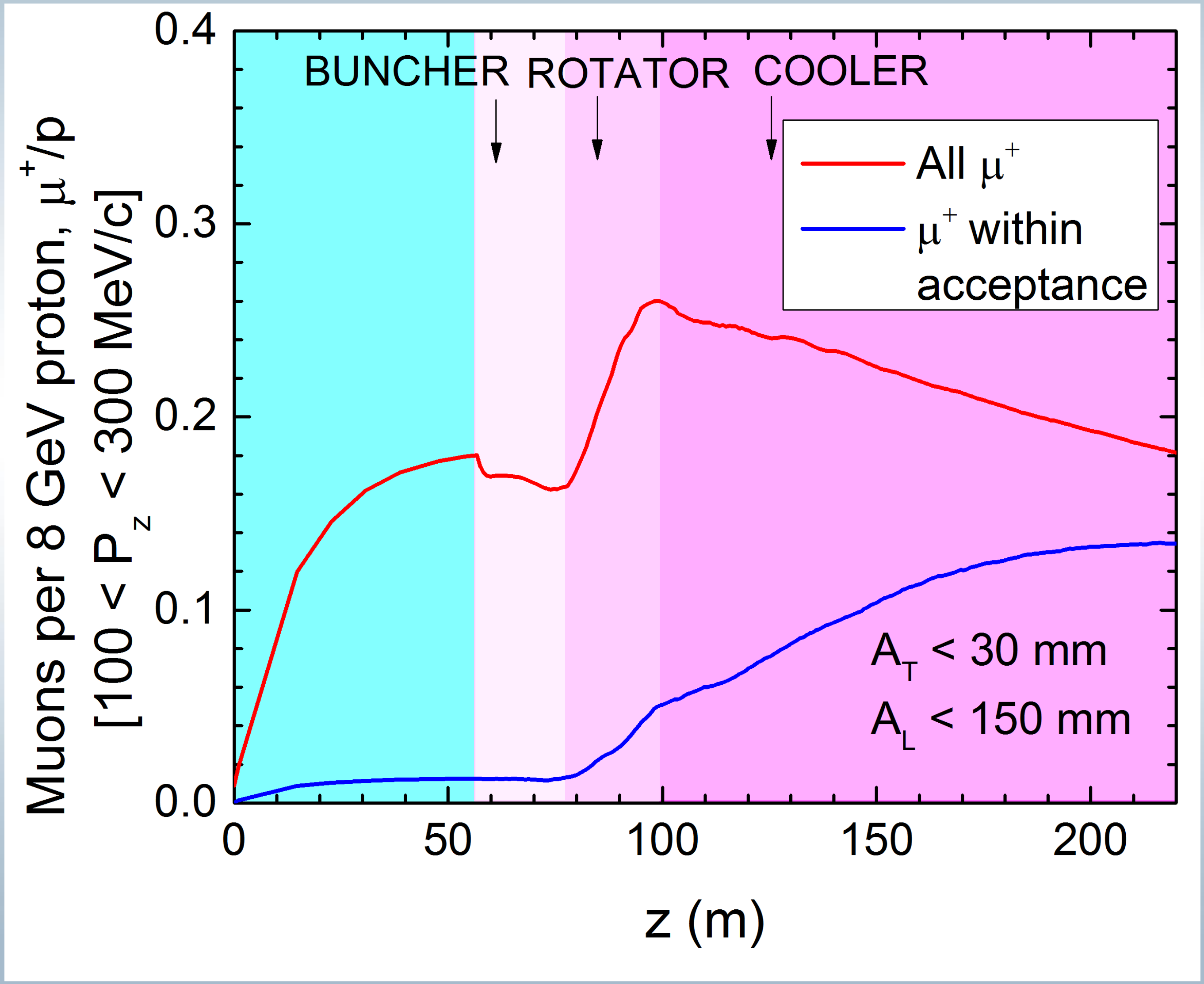
Beam after phase-rotation

- Captured beam:
  - Both signs can be captured simultaneously
  - bunches spaced by 3.1 ns at 325 MHz
  - μ/p≈0.25 per each sign per incident 8 GeV proton

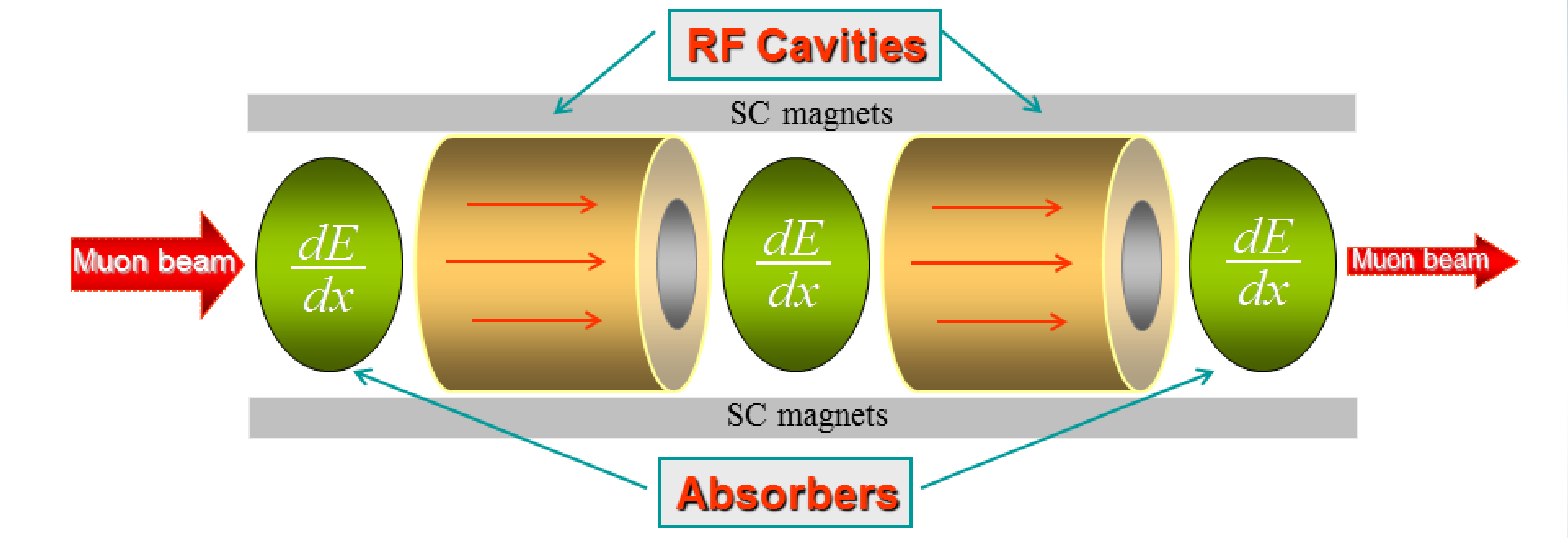




Muon production rate

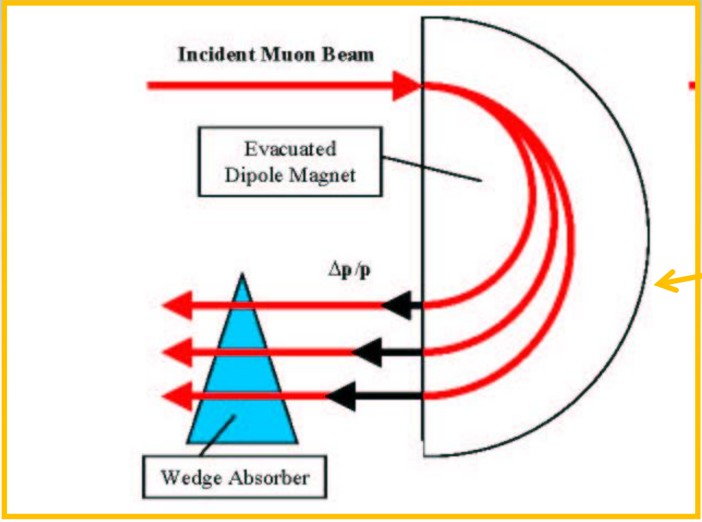


Ionization cooling



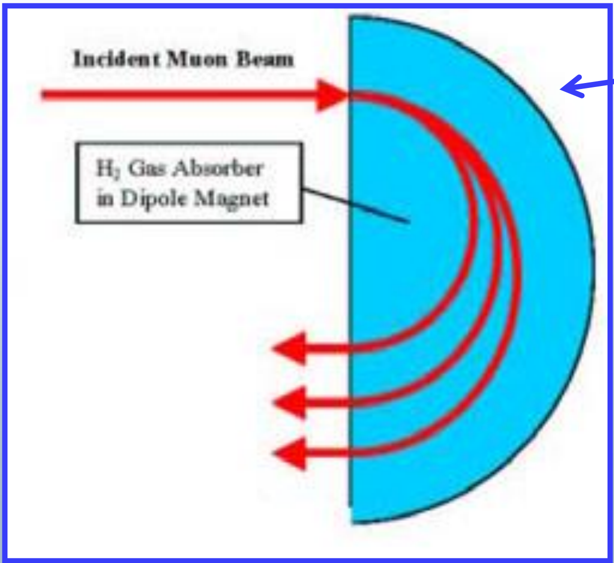
- Energy loss through ionization in absorbers
- rf cavities to compensate for lost longitudinal energy
- Note: This process cools the beam transversely, only!

Emittance exchange for 6D cooling



Concept 1: Generate dispersion and cool via emittance exchange in a wedge absorber

Concept 2: Energy loss dependence on path length in a continuous absorber



- Two concepts, same principle
- Dispersion is introduced to spatially separate muons of different momenta
- This study focuses on channels with discrete absorbers only!

Ionization cooling basics

•In the absorber: Energy loss is causing **cooling,** BUT multiple scattering is causing **heating**.

•A balance between the two processes gives:

$$\varepsilon_T^{\mathrm{eq}} = \left(\frac{dE}{ds}\right)^{-1} \frac{\beta_T (13.6\ \mathrm{MeV})^2}{2\beta m_\mu c^2 L_R}$$

L_R: Radiation length

E: Muon energy

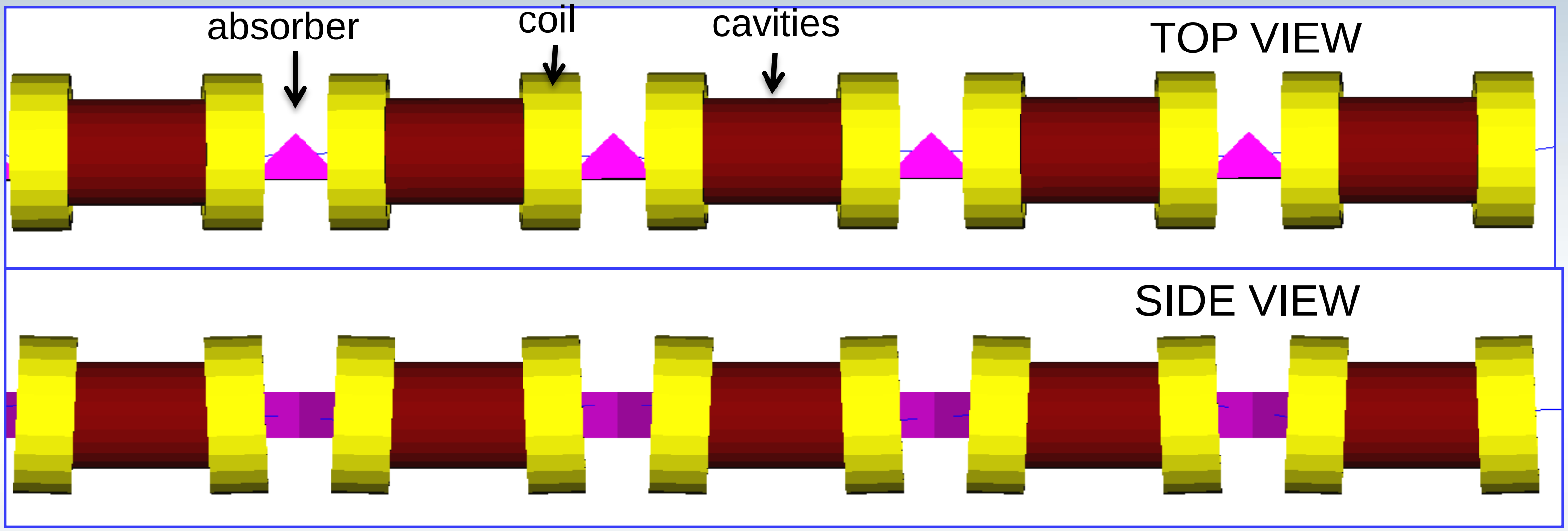
β_T: Transverse beta function

$\frac{dE}{ds}$: Energy loss

•Emittance can be controlled by:

- Material: Product of L_R and dE/ds should be large.
- Magnet strength: Transverse beta function must be small. Thus, we progressively taper the magnetic field towards higher values

Proposed cooling channel



- We considered a straight cooling scheme for a MC
- Idea originally proposed by Valeri Balbekov (Fermilab)
- Its simple geometry avoids several engineering challenges of previously considered schemes (rings or helix)

More details

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **18,** 031003 (2015)

Editor's suggestion!

Rectilinear six-dimensional ionization cooling channel for a muon collider: A theoretical and numerical study

Diktys Stratakis and Robert B. Palmer

Brookhaven National Laboratory, Upton, New York 11973, USA

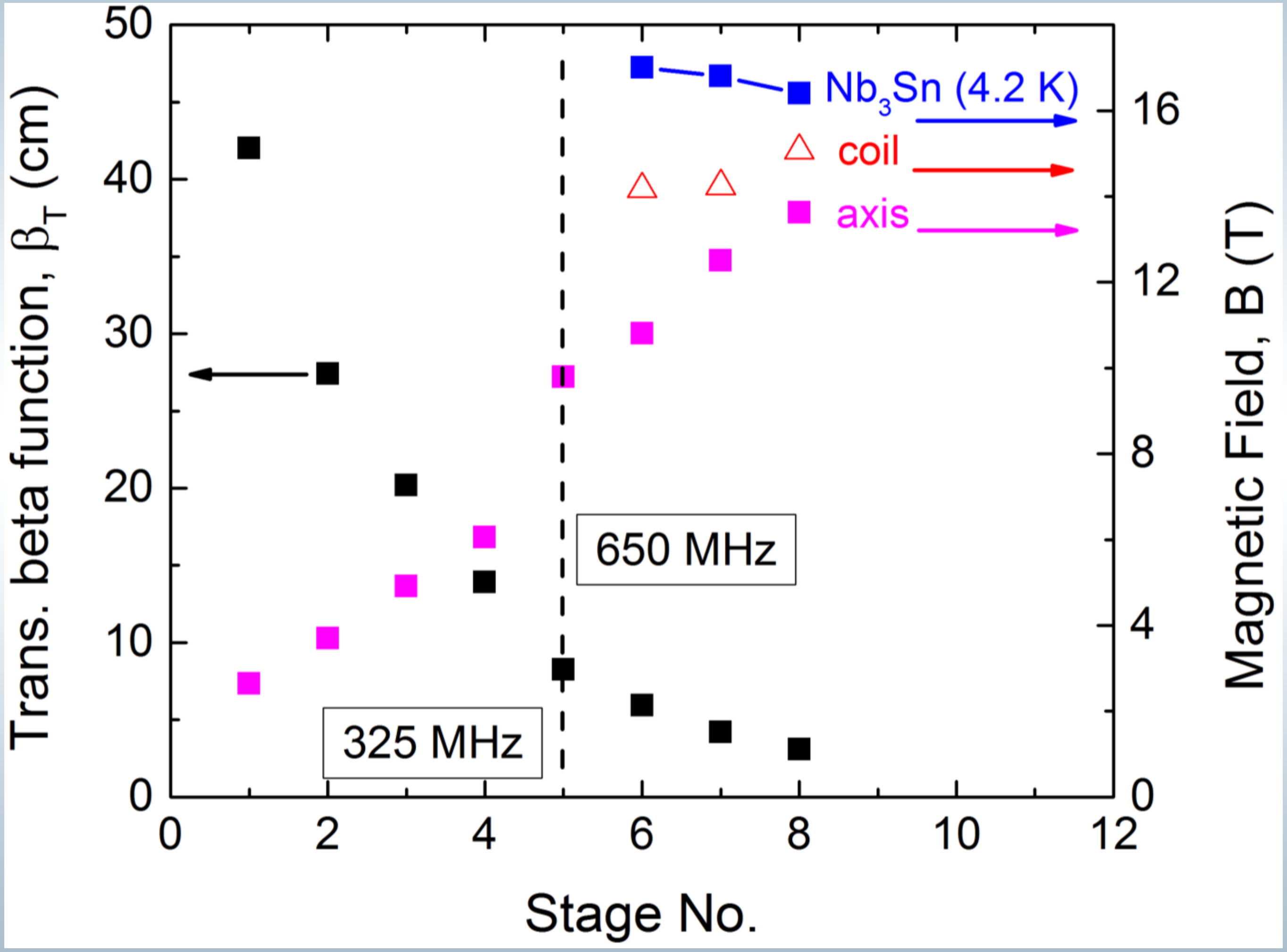
(Received 25 September 2014; published 6 March 2015)

A muon collider requires a reduction of the six-dimensional emittance of the captured muon beam by several orders of magnitude. In this study, we describe a novel rectilinear cooling scheme that should meet this requirement. First, we present the conceptual design of our proposed scheme wherein we detail its basic features. Then, we establish the theoretical framework to predict and evaluate the performance of ionization cooling channels and discuss its application to our specific case. Finally, we present the first end-to-end simulation of 6D cooling for a muon collider and show a notable reduction of the 6D emittance by 5 orders of magnitude. We find good agreement between simulation and theory.

DOI: 10.1103/PhysRevSTAB.18.031003 PACS numbers: 29.20.Ej, 41.75.Lx

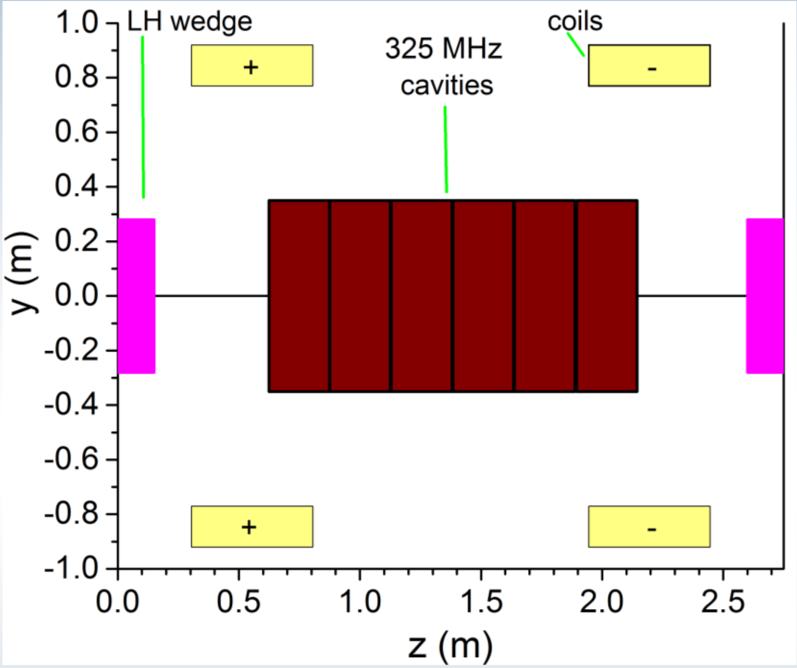
Download:
http://journals.aps.org/prstab/abstract/10.1103/PhysRevSTAB.18.031003

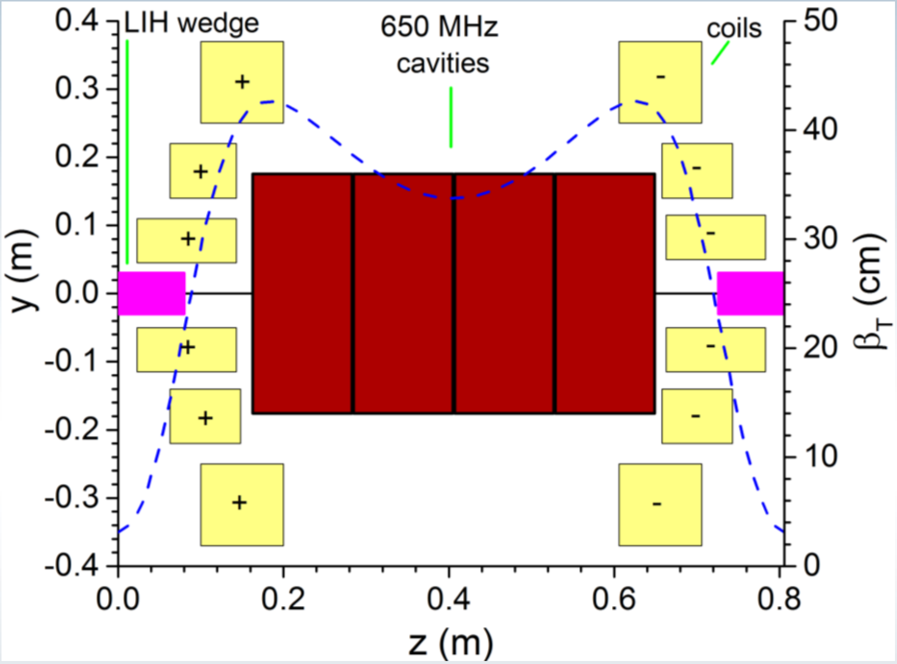
Tapered lattice design: 8 stages



Magnet limits:
https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

Two extremes: First & last cooling stage





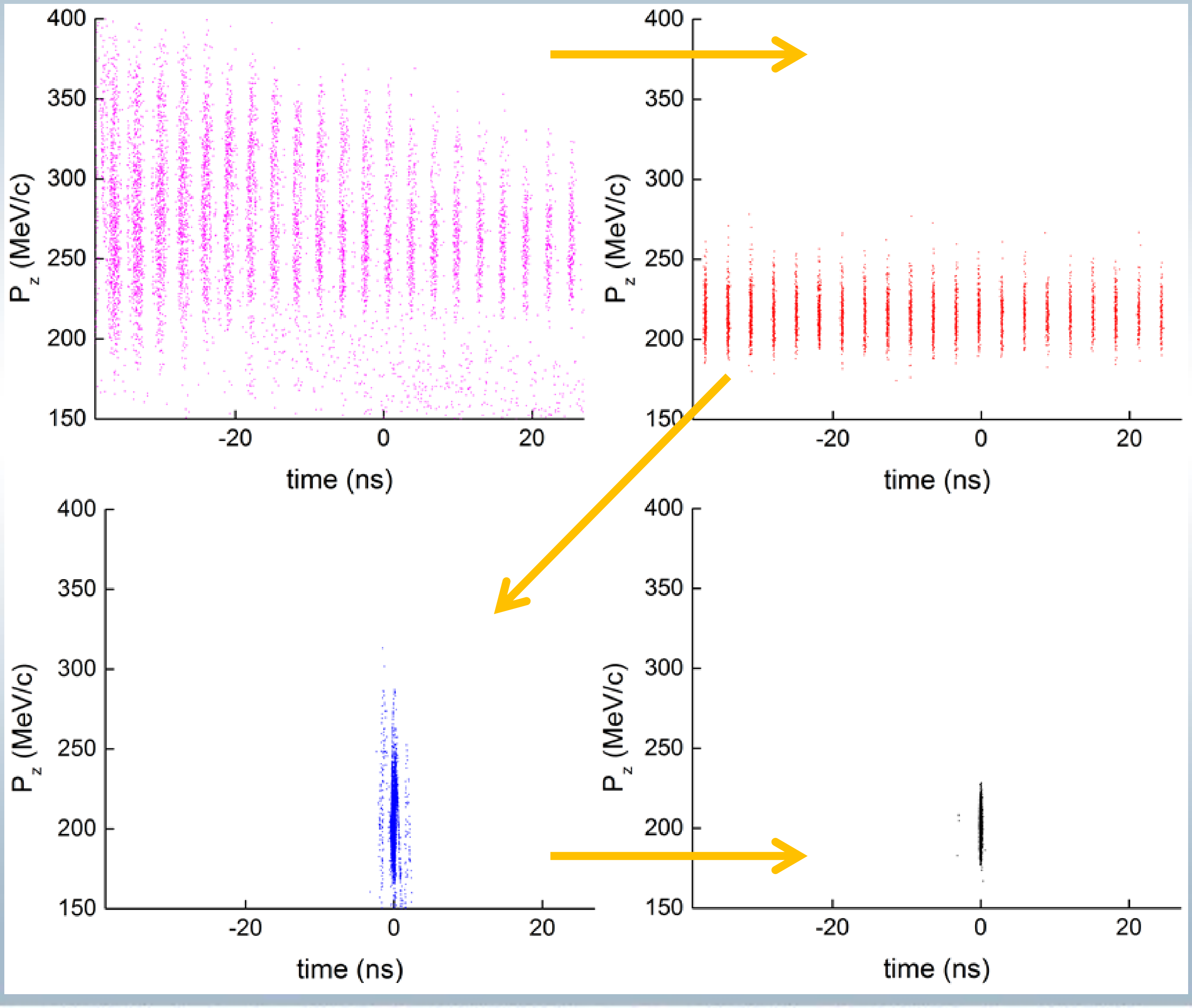
EARLY STAGE OF COOLING

- 275 cm long
- Coils far
- 325 MHz
- Axial B ~ 3 T
- Beta ~ 40 cm

LATE STAGE OF COOLING

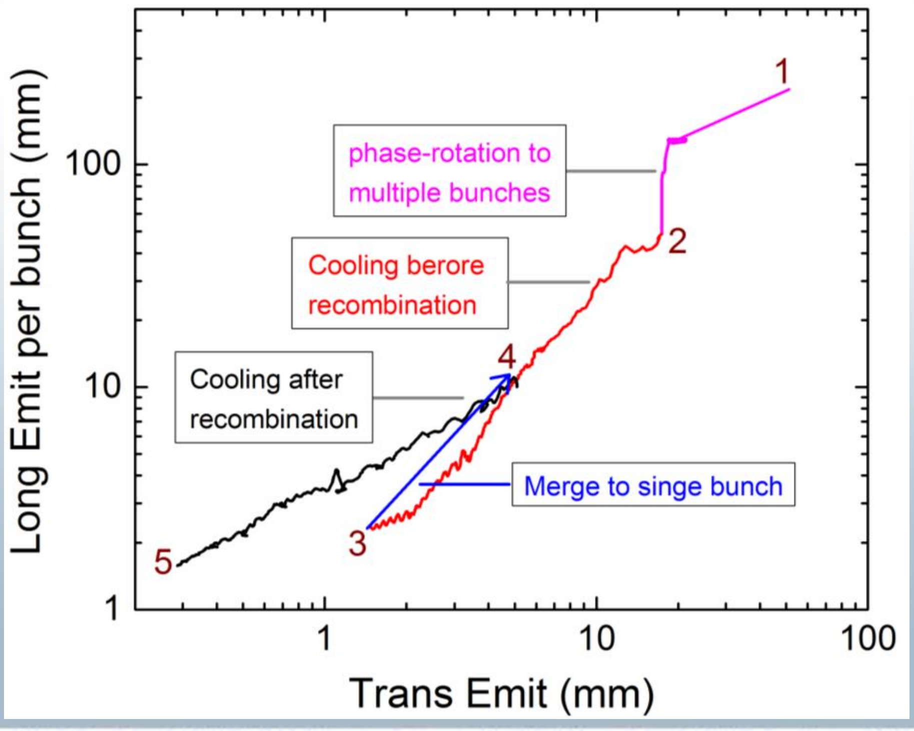
- 80 cm long
- Coils near axis
- 650 MHz
- Axial B ~ 12 T
- Beta ~ 3 cm

Simulation results (1)



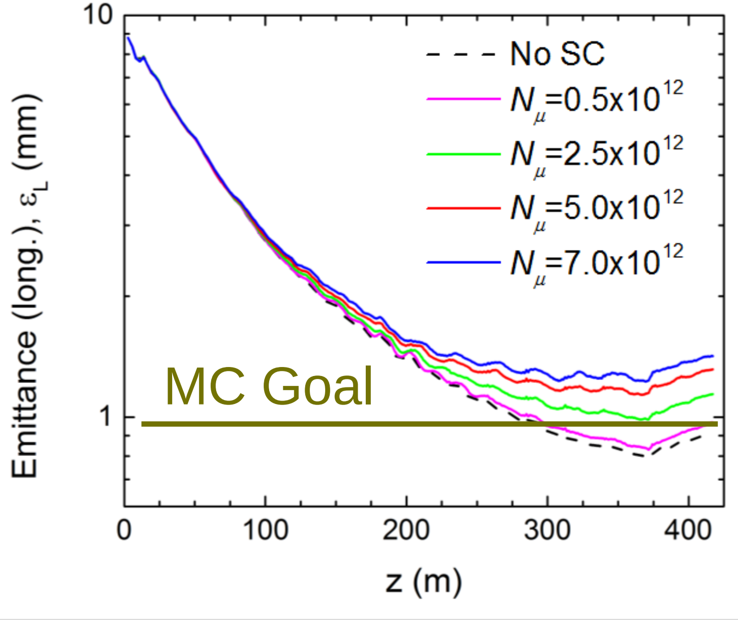
Simulation results (2)

- End-to-end simulation starting from the target (point 1)
- Reduction of the 6D emittance by several orders of magnitude (point 5)
- Desired emittances for Higgs factory delivered!

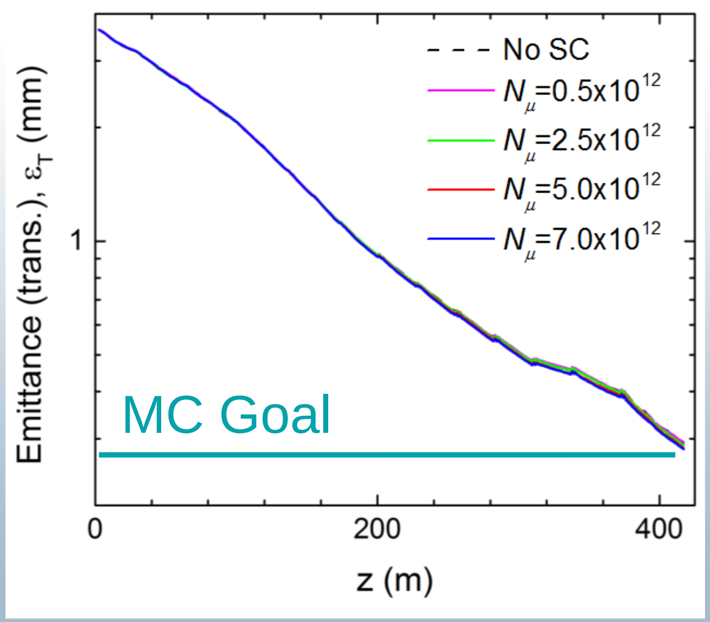


Influence of space-charge (SC)

- At the end of cooling, $5x10^{12}$ muons are squeezed within a 2 cm rms bunch length. There is a concern for SC effect
- We examined the influence of SC fields on cooling
- SC causes particle loss & longitudinal emittance growth

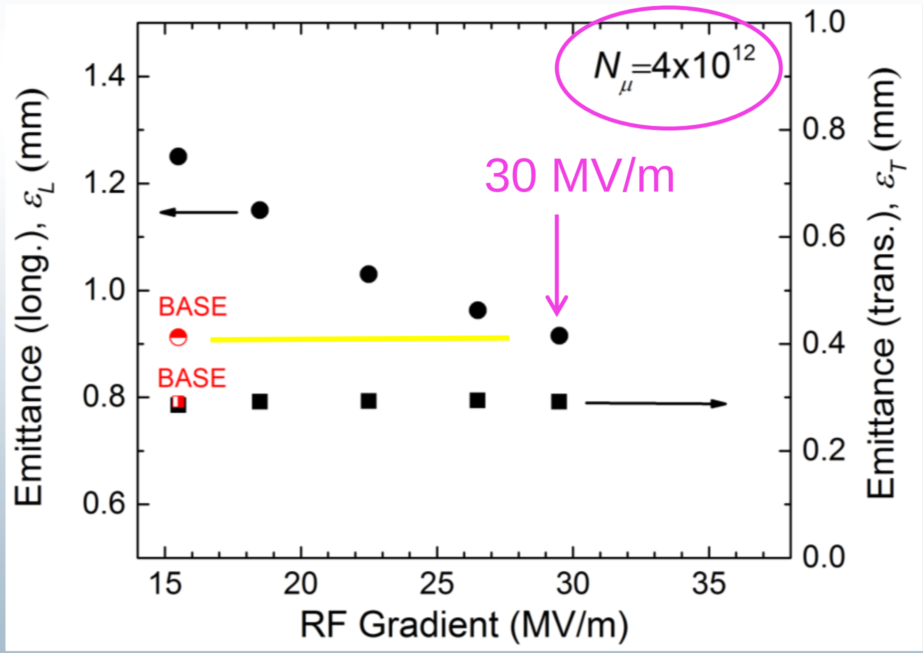


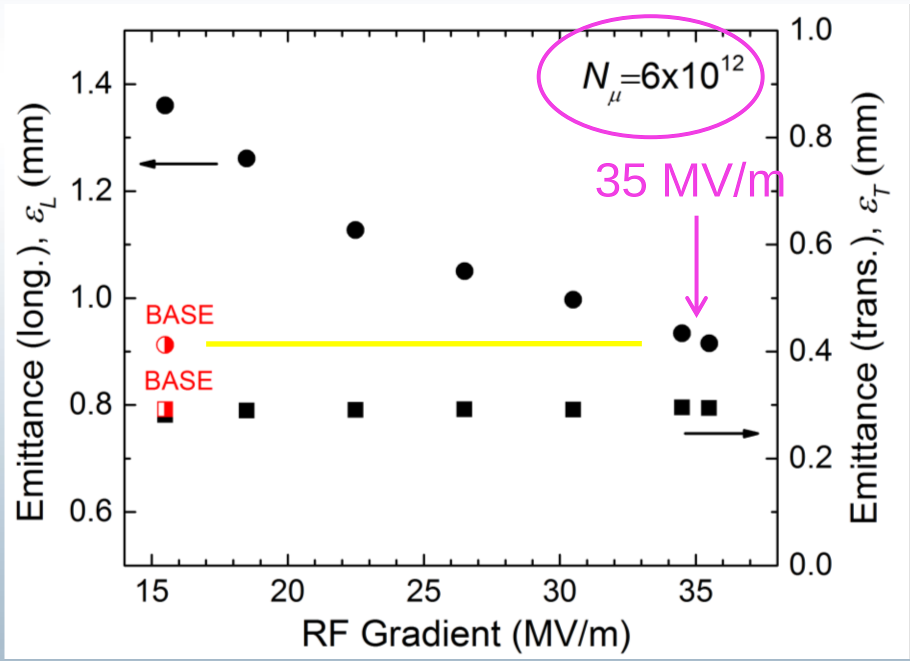
WARP Simulation



Space-charge compensation (1)

- Increasing the rf gradient can compensate SC effect
- The needed compensation gradient is coupled to the beam intensity

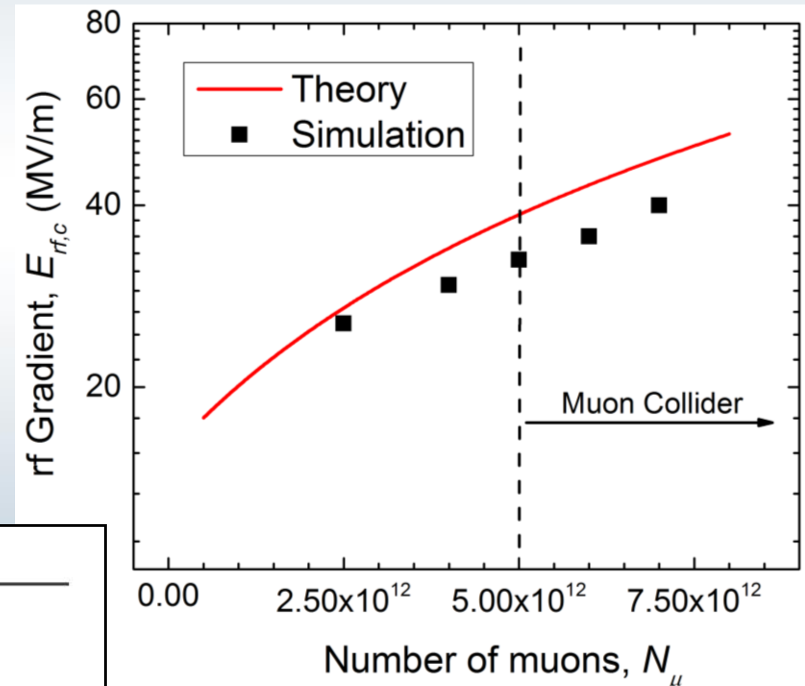




Space-charge compensation (2)

- For a MC to obtain a $\varepsilon_L < 1.0$ mm the rf gradient of a 805 MHz cavity needs to surpass 32.5 MV/m
- Can be a problem (next slide)
- Required compensation gradient from theory:

$$\boxed{E_{rf,c} = \frac{e N_0 g_0 c}{4\pi\varepsilon_0 \sqrt{2\pi}\gamma^2 \sigma_z^3 (2\pi f n \cos\varphi)^2}}$$



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 18, 044201 (2015)

Editor's suggestion

Influence of space-charge fields on the cooling process of muon beams

Diktys Stratakis and Robert B. Palmer
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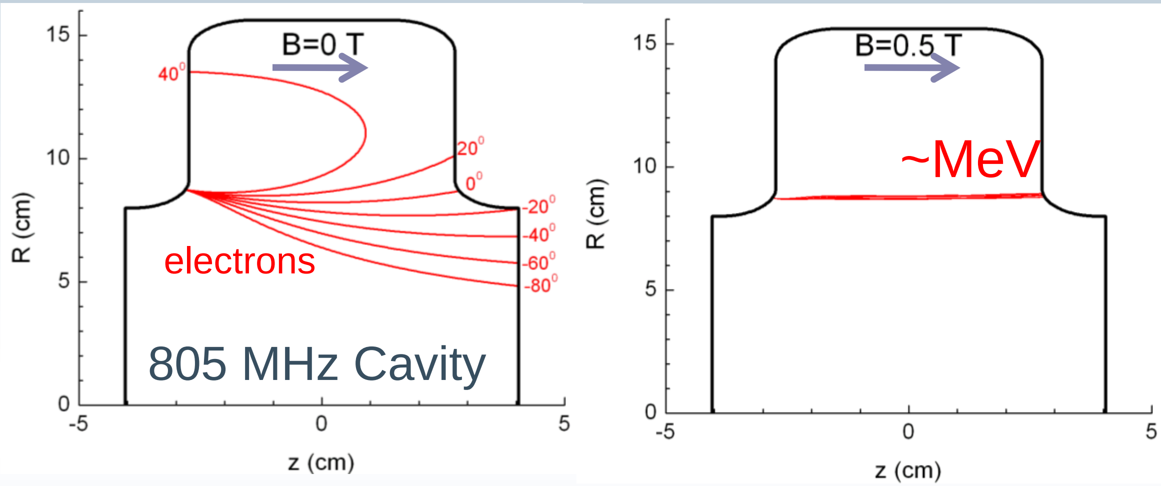
David P. Grote
Lawrence Livermore National Laboratory, Livermore, California 94550, USA

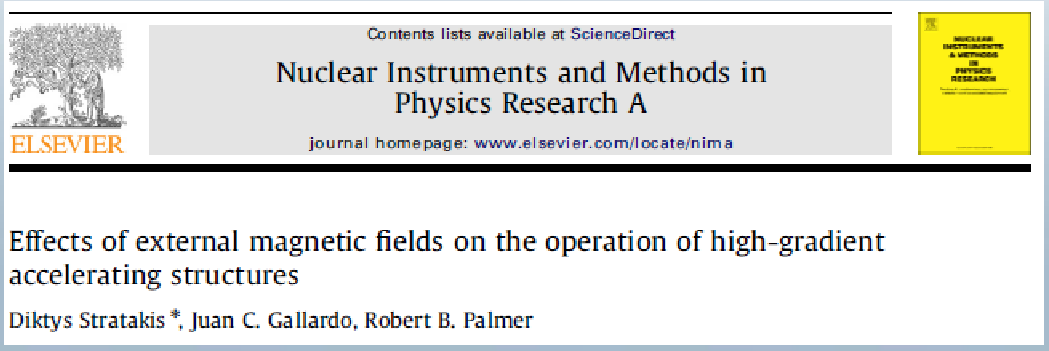
(Received 15 November 2014; published 7 April 2015)

A challenge: rf operation in B-fields



Damage on a 805 MHz rf cavity immersed in a multi-T magnetic field.

- Numerical simulations predict that the copper surfaces of a rf cavity may damaged when B> 1T


Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

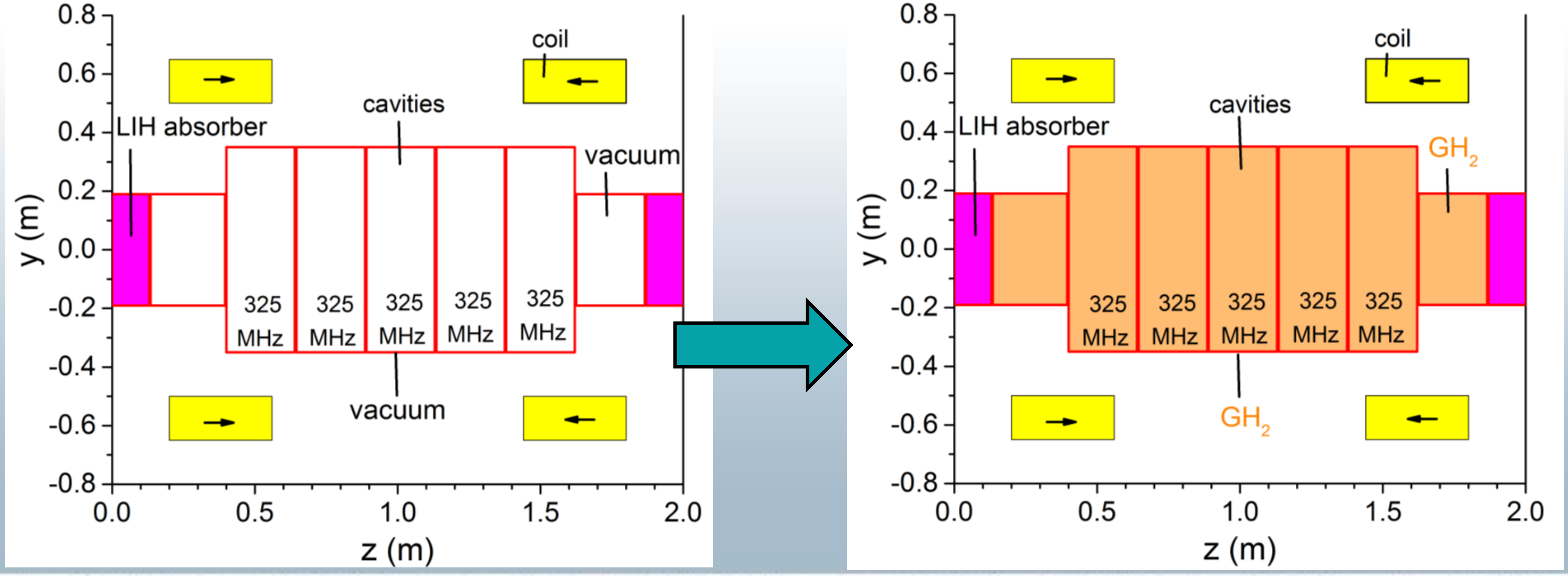
ELSEVIER

Effects of external magnetic fields on the operation of high-gradient accelerating structures

Diktys Stratakis *, Juan C. Gallardo, Robert B. Palmer

Hybrid solution

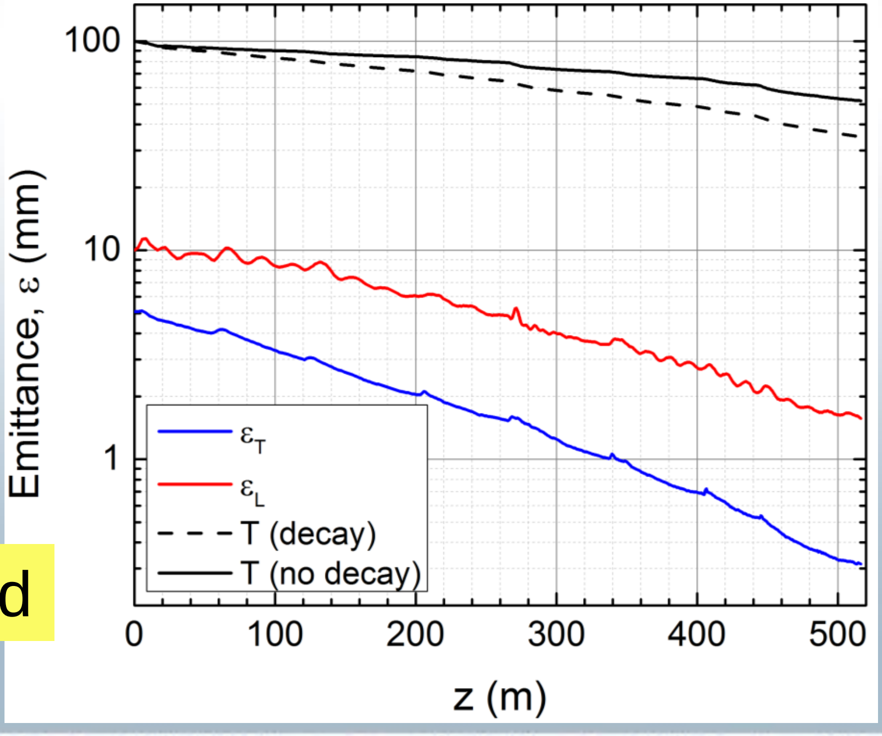
- The gradient of a gas filled cavity showed no magnetic field dependence in a solenoidal field up to 3 T.
- Key Idea: Utilize gas filled cavities in a rectilinear channel. Majority of cooling in LiH and use gas only to protect rf cavity from the high-field.



Lattice performance

- Essentially, the same performance as an equivalent channel with vacuum cavities
- BUT there remains considerable work to do before a hybrid channel can be considered a validated cooling channel option.

Hybrid



Future work – Open problems

- Energy deposition studies
  - Study on the target, chicane and rest of the channel
- Improve design of muon capture channel
  - Increase performance
- Reduce length of the cooling channel
  - Existing channel for a MC is 900 m ...
- Physics problems
  - Wakefields, absorbers, plasma loading
- Engineering problems
  - Magnets, cavities in magnetic fields, …

Summary

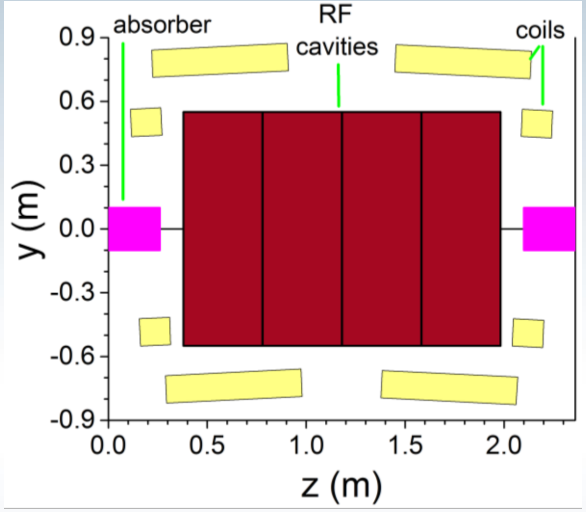
- Presented a scheme to collect & transport intense muon beams.
- Simulations show that it produces 0.25 μ/p with a relatively good degree of efficiency (~60%)
- Presented a simple scheme for ionization cooling
- Simulations predict that is capable to reduce the 6D emittance by at least five orders of magnitude thus satisfying the needs of a Higgs factory.
- The influence of space-charge fields on the cooling process was thoroughly examined
- A hybrid solution with gas filled cavities was presented

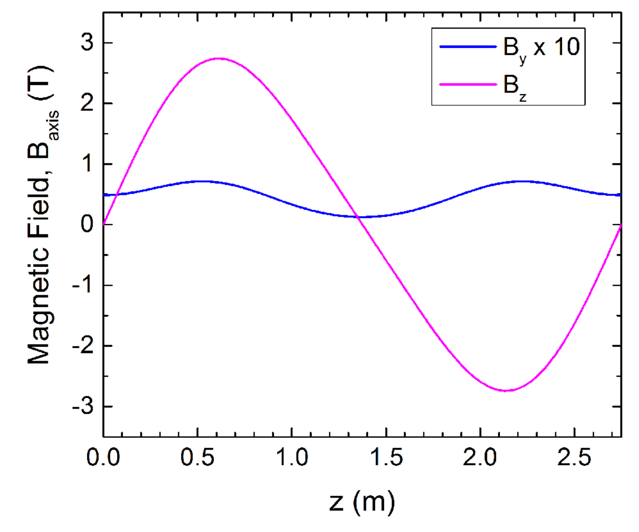
Acknowledgement

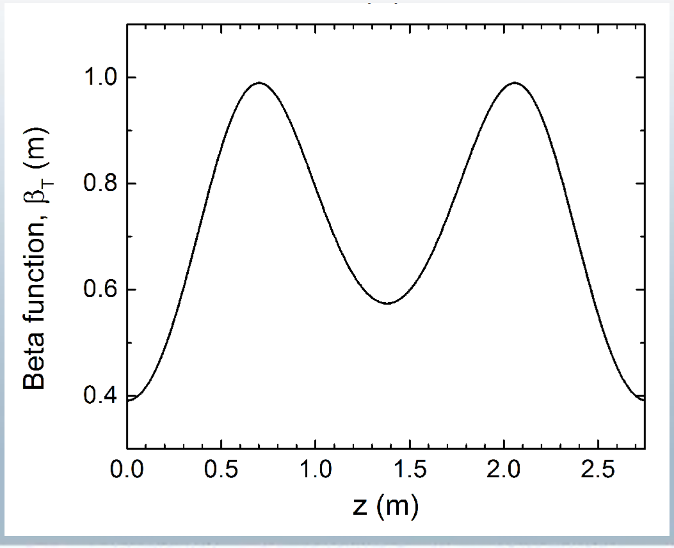
- Special thanks to all members of the Muon Accelerator Program community

Cooling channel: How it works

- Coils tilted to create a B_y component
- This leads to dispersion → High momentum particles pass through more material → 6D cooling
- Absorber is placed at the point where β_T is minimum

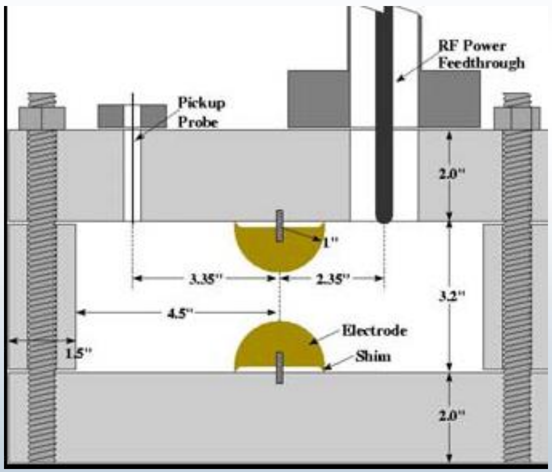


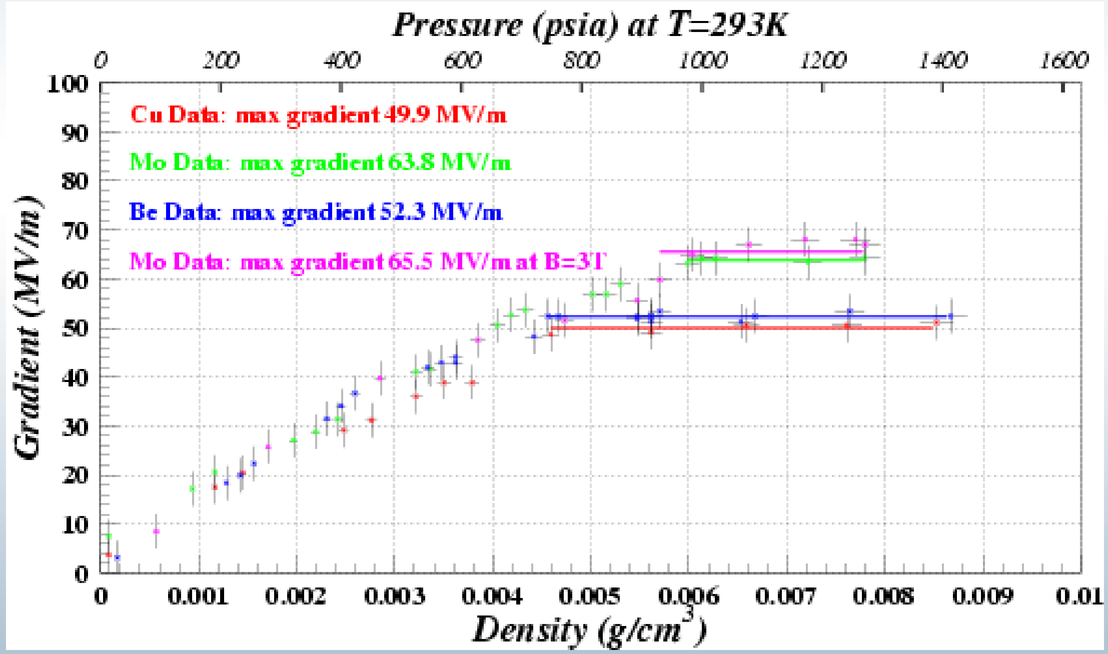




Back-up : Gas-filled cavities

•The gradient of a gas filled cavity showed no magnetic field dependence in a solenoidal field up to 3 T.



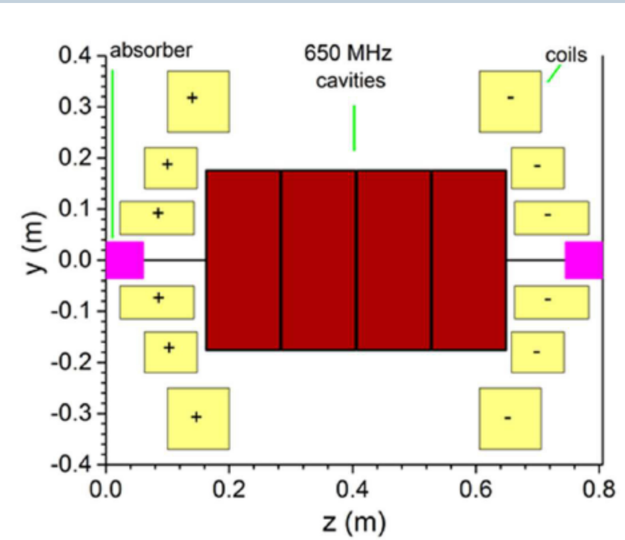


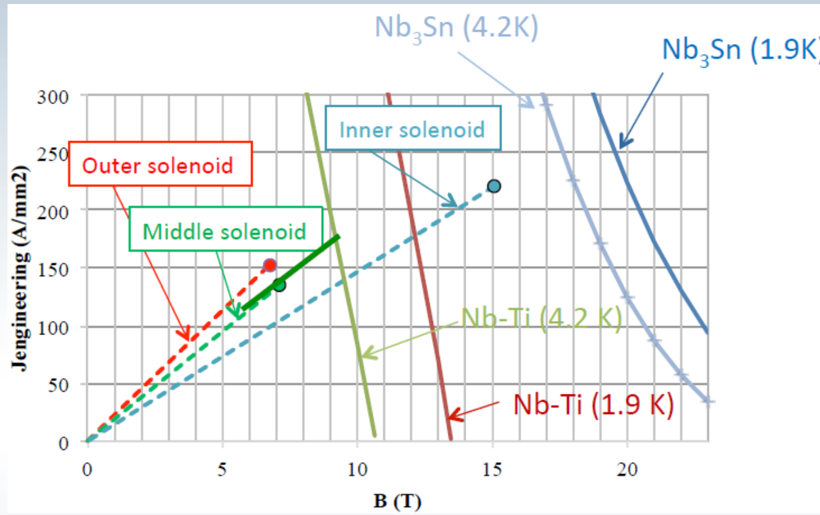
P. Hanlet et al., EPAC 2006, p. 1364 (2006)
M. Chung et al., PRL 111, 184802 (2013)

Back up: Muon Collider Parameters

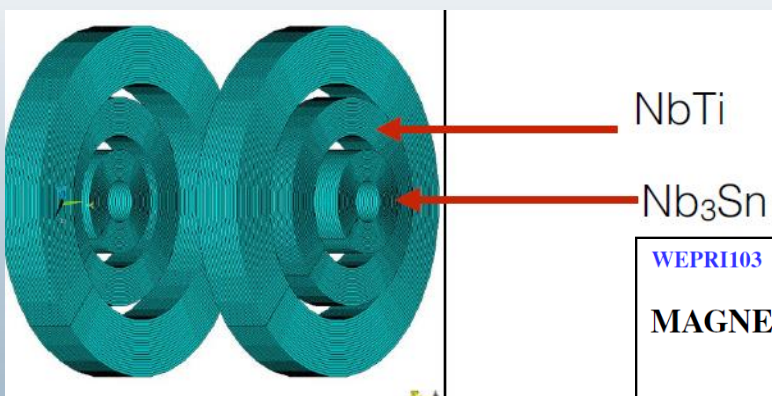
Muon Collider Parameters									
		Higgs Factory		Top Threshold Options		Multi-TeV Baselines			
Parameter	***Units***	*Startup Operation*	*Production Operation*	*High Resolution*	*High Luminosity*			*Accounts for Site Radiation Mitigation*
CoM Energy	TeV	0.126	0.126	0.35	0.35	1.5	3.0	6.0
Avg. Luminosity	$10^{34}cm^{-2}s^{-1}$	0.0017	0.008	0.07	0.6	1.25	4.4	12
Beam Energy Spread	%	0.003	0.004	0.01	0.1	0.1	0.1	0.1
Higgs* or Top$^+$ Production/10^7sec		3,500*	13,500*	7,000$^+$	60,000$^+$	37,500*	200,000*	820,000*
Circumference	km	0.3	0.3	0.7	0.7	2.5	4.5	6
No. of IPs		1	1	1	1	2	2	2
Repetition Rate	Hz	30	15	15	15	15	12	6
β^*	cm	3.3	1.7	1.5	0.5	1 (0.5-2)	0.5 (0.3-3)	0.25
No. muons/bunch	10^{12}	2	4	4	3	2	2	2
No. bunches/beam		1	1	1	1	1	1	1
Norm. Trans. Emittance, ε_{TN}	π mm-rad	0.4	0.2	0.2	0.05	0.025	0.025	0.025
Norm. Long. Emittance, ε_{LN}	π mm-rad	1	1.5	1.5	10	70	70	70
Bunch Length, σ_s	cm	5.6	6.3	0.9	0.5	1	0.5	0.2
Proton Driver Power	MW	$4^\#$	4	4	4	4	4	1.6

Back up: Magnet feasibility (last stage)





	% of the load line at operational current		
	Inner solenoid	Middle solenoid	Outer solenoid
Nb-Ti @ 4.2 K	-	76%	74%
Nb-Ti @ 1.9 K	-	59%	58%
Nb3Sn @ 4.2 K	88%	-	-
Nb3Sn @ 1.9 K	81%	-	-



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MAGNET DESIGN FOR A SIX-DIMENSIONAL RECTILINEAR COOLING CHANNEL - FEASIBILITY STUDY*

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Back up: Buncher & rotator parameters

Match to 325 MHz*	Len. (m)	No. of RF	f (MHz)	RF grad. (MV/m)	B axis (T)
Buncher	21	28	490.0 to 365.0	0.0 to 15.0	2.0
Rotator	24	32	364.0 to 326.0	20.0	2.0
Total	45	60			

*Currently under study